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Cost of Cycling Fossil Power Plants – What Do You Need to Know and Why?

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ABSTRACT

Competition in the electric utility business and high penetrations of wind and solar power is having a far-reaching impact including on the operations of the conventional generators on the power system. A requirement for meeting this challenge is for utilities to better understand the true nature of their costs. Based on that understanding, utilities then need to develop operating and strategic plans to better manage their assets, minimize costs, and maximize return on investments. One area where the understanding of the underlying nature of costs is particularly weak is power plant operation and maintenance (O&M), which includes a wide variety of activities such as equipment monitoring, replacement, and upgrading. A major root cause of this increase in O&M cost for many fossil units is unit cycling. Utilities have been forced to cycle aging fossil units that were originally designed for base load operation.

In this paper, we address the following two questions: (1) Why do we need to understand true power plant cycling costs? (2) What can and should we do once we understand these costs?

WHAT IS PLANT CYCLING?

Cycling refers to the operation of electric generating units at varying load levels, including on/off and low load variations, in response to changes in system load requirements. Figure 1 below shows various "cycling" operating modes at a power plant.

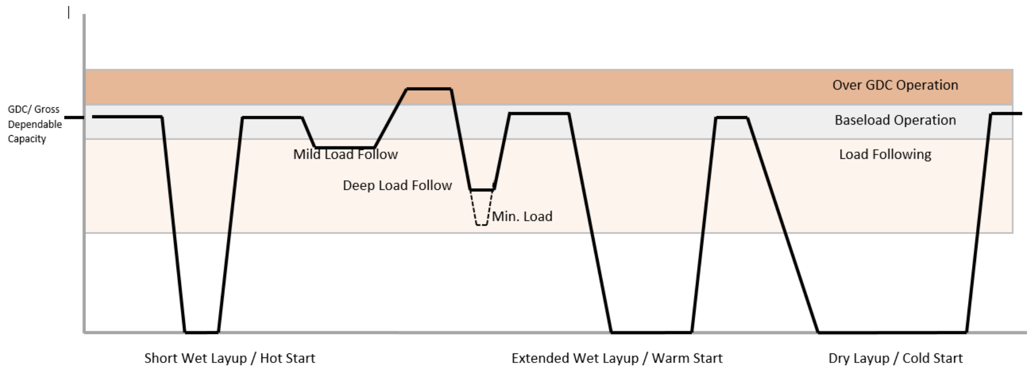

Figure 1 — Power plant cycling operation modes.

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A traditional fossil steam unit or a combined cycle plant has offline periods wherein the plant may be in a wet or dry layup, with offline hours determining the start type – hot, warm or cold. In addition to the different start types, the plant may be forced to operate above its maximum rating or gross dependable capacity (GDC). Units with tight margins on waterwall circulation rate may result in phosphate hideout. In other units, the furnace exit gas temperature may increase ever so slightly resulting in accelerated damage in the steam-touched pressure part regions of a boiler. Equally important operating mode to consider is the load following of these units, which may be mild or significant, depending on the megawatt (MW) range of the cycle. Every time a power plant is turned off and on or operated in load following operation, the boiler, steam lines, turbine, and auxiliary components go through unavoidably large thermal and pressure stresses, which cause damage. This damage is made worse by the phenomenon we call creep-fatigue interaction.

Creep and fatigue are terms commonly used in engineering mechanics. Creep is time-dependent change in the size or shape of a material due to constant stress (or force) on that material. In fossil power plants, creep is caused by continuous stress that results from constant high temperature and pressure in a pipe or tube occurring during steady-state base load operation. Fatigue is a phenomenon leading to fracture (failure) when a material is under repeated, fluctuating stresses. In a fossil power plant, such fluctuating stresses result from large transients in both pressures and temperatures. These transients typically occur during cyclic operation.

Because base load fossil units are designed to operate in the creep range, they experience increased outages when they are additionally subjected to cycling-related fatigue. The term creep-fatigue interaction suggests that the two phenomena (creep and fatigue) are not necessarily independent, but act in a synergistic manner to cause premature failure. In fact, materials behave in a complex manner when both types of stresses occur. Creep-fatigue interaction is one of the most important phenomena contributing to component failures and can have a detrimental effect on the performance of metal parts or components operating at elevated temperatures. It has been found that creep strains (i.e. mechanical deformation as a result of stress) can reduce fatigue life and that fatigue strains can reduce creep life.

A set of American Society of Mechanical Engineers (ASME) creep-fatigue interaction curves is given in Figure 2. This figure reveals how creep fatigue interaction affects the life expectancies (i.e., time to failure) of three types of materials. Most power plants have been built using ferritic steels, such as 2-1/4% chrome/1% molybdenum steel which is shown on Figure 2.

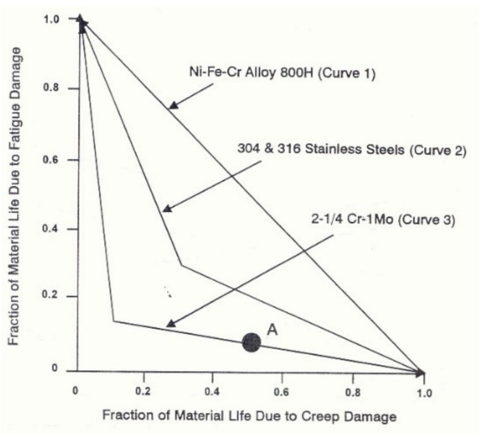

Figure 2 — Creep Fatigue Interaction Design Curves for Several Materials.

We would like to highlight the implication of the non-linear relationship of this curve. A new power plant component can withstand a lot of fatigue damage before it fails. However, a material that has gone through 50% of life creep damage (e.g., base load operation), as shown by Point A in the exhibit, reaches end of life with only about 10% fatigue damage. Older units that were designed for and used for base load operation over a number of years are very susceptible to component failure when they are forced to cycle on a regular basis. In general, this type of material that experiences both creep and fatigue will fail much faster than if it experiences creep alone.

Relating this discussion to power plants, if an older, base loaded plant (that used to have three to six starts per year and is at 40 to 80% design life creep damage) is now dispatched to operate at 50 starts per year, it may take only 2 to 6 years to accumulate the 10 to 20% total fatigue damage needed to cause component failures.

Thus, while cycling-related increases in failure rates may not be noted immediately, critical components will eventually start to fail. Shorter component life expectancies will result in higher plant equivalent forced outage rates (EFOR) and/or higher capital and maintenance costs to replace components at or near the end of their service lives. In addition, it may result in reduced overall plant life. How soon these detrimental effects will occur will depend on the amount of creep damage present and the specific types and frequency of the cycling.

WHY ANALYZE CYCLING DAMAGE AND COSTS?

Knowledge of costs accurately and, ideally, in real-time, is critical to the competitive power business. During high profit times, operations should be able to react to high market prices and ramp load faster as well as operate at or above a unit's maximum rating. During low power price periods, an operator must decide to either shutdown and incur significant cycling damage or incur fuel cost at a loss and stay at minimum load. Other questions include: What, in terms of fuel costs and cycling costs, is the cheapest combination of units to meet system load? Can I reduce the cost of base-load power in a long-term power sales contract and by how much if I reduce the number of unit cycles? Can one transfer the high cost to cycle to other plants at utilities with which you may compete in the marketplace? Do I maintain my plant equipment based on operating time or based on number of accumulated cycles?

The authors have analyzed the cycling costs in nearly 500 power generating plants, in North America, Europe and Australia. The analyzed power plants have included conventional coal, oil, and gas fired units ranging from 15 MW to 1300 MW in size, from subcritical drum-type or once through to supercritical once through units with varying turbine, boiler, and balance of plant manufacturers. The units also have a range of designs and operational regimes, from those designed for cycling with turbine bypass systems to units designed for base-loaded operations, to those subjected to heavy cyclic operations, such as two-shifting and AGC control to extended base-loaded operations at and above a unit's maximum continuous rating operation (MCR). Regardless of type, each unit in the fleet should have its costs analyzed so that the utility system can be dispatched on a similar cost basis (i.e., all units placed on a level playing field). This allows some of the higher heat rate units that may have low costs to cycle more generation and to provide a valuable cycling service to a fleet of plants with low cost base-loaded units that are expensive to cycle.

POWER PLANT CYCLING COSTS AND IMPACTS

Cost of cycling estimates are uncertain; however, this uncertainty can be evaluated and bounded. The uncertainties arise from the fact that the cycling damage mechanisms leading to component failures are complex and usually involve multi-year time lagging. Many of the equipment damage effects of cycling discussed above crop up over time. The time delay relationship between an added unit cycle and accelerated component failure might range from several weeks to several years. This fact raises the strategic dilemma as follows: Should we minimize today's costs by cycling the fossil units a lot to save on today's energy costs, and not worry about the longer-term damage effects of cycling?

Damage Mechanisms & Damage Modeling

Definitions of cycling have varied from on/off starts (normally defined as hot, warm, and cold starts) and two-shifting to load cycling and high frequency load variations. Inclusion of all cyclic operations is critical to proper analysis. Many units do only a few starts but provide a large amount of intra hour load following and AGC services that significantly add to a unit's cyclic damage and must be accounted for. Hot starts are typically defined to have very high (370°C - 480°C) boiler/turbine temperatures and less than 8 to 12 hours offline. Warm starts have warm boiler/turbine temperatures (typically above the fracture appearance transition temperatures (FATT), in the range of 120°C - 370°C) and 12 to 48 hours offline. Cold starts are ambient temperature starts with boiler turbine temperatures below FATT (about 120°C or less) and typically more than 48 to 120 hours offline. These definitions may vary due to unit size and dispatcher/Independent System Operator (ISO) definitions. The definitions may also require adjustment due to rapid boiler cooling while turbine components remain much hotter, as this can dramatically effect damage and costs.

Cycling damage is very unit specific and dependent on design and unit operational practices. Relative damage resulting from different categories of cycling operations is shown in Figure 3.

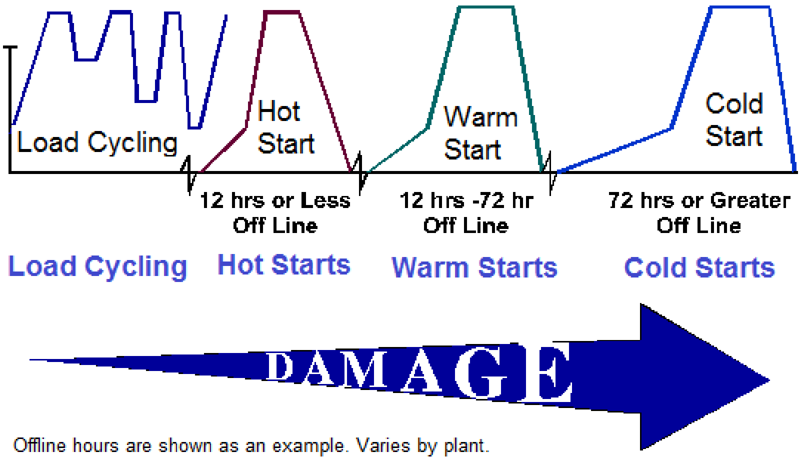

Figure 3 — Relative damage per cycling transient.

The vast number of unit types, equipment manufacturers, balance of plant types, and operational regimes makes the cycling costs difficult to generally categorize without significant experience and detailed analysis. Damage models have been developed that include creep and fatigue and their interaction for each unit type. These models account for cyclic operation, base-loaded operation, and operation above GDC damage for various key components, such as boilers (including tubing), turbines, and generators at conventional fossil units, hydro and pumped hydro plants, gas turbines, and heat recovery steam generators (HRSGs). These models are calibrated with plant signature data (temperatures and pressures) for key unit components operating during typical load transients. The model validation process has included the assessment of key components with finite element analysis and creep/fatigue analysis methods to determine remaining useful component life, augmented by information from thousands of laboratory failure and stress analyses of power plant components. These life analyses of key high cycling cost components are statistically calibrated to the failure history of these components. Traditional, uncalibrated engineering fatigue and creep analyses, however ambitious and expensive, are rarely useful and often misleading in predicting cycling costs.

Table 1 presents the damage mechanisms and failures most often found in cycling boilers and turbines, and from normal boiler and feedwater chemistry. Damage manifests itself in terms of past and future maintenance and capital replacements, as well as forced outages and derates when cycling or because of high load operation. There are several damage mechanisms that adversely impact plant equipment, including fatigue, creep-fatigue interaction, corrosion fatigue, chemistry transients and deposition, and mechanical wear. Figure 4 shows an example of one of the most common damage mechanisms, corrosion fatigue.

Table 1 — Effects of Cycling on Plant Equipment/Systems (partial list)

Boiler Failures due to Cycling	Turbine Effects due to Cycling	Chemistry Effects due to Cycling
• Boiler Seals Degradation • Tube Rubbing • Boiler Hot Spots • Drum Humping/Bowing • Downcomer to Furnace Subcooling • Expansion Joint Failures • Cracking of Boiler Tubes in Furnace Corners • Cracking of Tube to Buckstay/Tension Bar	• Water Induction to Turbine • Increased Thermal Fatigue Due to Steam Temperature Mismatch • Steam Chest Fatigue Cracking • Steam Chest Distortion • Bolting Fatigue Distortion/Cracking • Blade, Nozzle Block, Solid Particle Erosion • Rotor Stress Increase • Rotor Defects (Flaws) Growth	• Corrosion Fatigue • Oxygen Pitting • Corrosion Transport to Boiler and Condenser • Air, Carbon Dioxide Oxygen Inleakage • NH_3 – Oxygen Attack on Admiralty Brass • Grooving of Condenser/Feedwater Heater Tubes at Support Plates

• Cracking of Tube to Windbox Attachment • Tube to Header cracking • Tube to Burner fatigue cracking • Cracking of Membrane to Tube • Cracking of Economizer Inlet Header • Cracking of Header Ligament	• Seals/Packing Wear/Destruction • Blade Attachment Fatigue • Disk Bore and Blade Fatigue/Cracking • Silica and Copper Deposits • Lube Oil/Control Oil Contamination • Shell/Case Cracking • Wilson Line Movement • Bearing Damage • Reduced Life	• Increased Need for Chemical Cleaning • Phosphate Hideout Leading to Acid and Caustic Attack • Silica, Iron, and Copper Deposits • Out of Service Corrosion

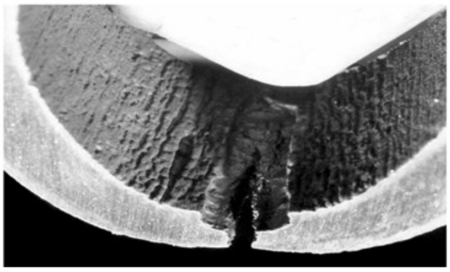

Figure 4 — Corrosion Fatigue Failure

Our damage model is intended to provide information on the cycling-related damage for the entire unit. It is founded on physical models and uses plant temperature and other real-time thermocouple data ("signature data") to provide cross validation with MW changes, but requires hourly MW operation data to estimate damage. In addition, hourly MW data provide an accurate history of past unit operations. The damage model accounts for creep damage, fatigue damage, erosion, corrosion, and all other types of damage that are known to occur in most power plants.

The damage model validation process has included the assessment of key components with finite element analysis and creep/fatigue analysis methods to determine remaining useful component life, augmented by information from laboratory failure and stress analyses of power plant components. These life analyses of key high cycling cost components are statistically calibrated to the failure history of these components. Thus, all damage is calibrated to actual plant costs and these costs must back predict or back cast historical costs to be validated. Traditional, uncalibrated engineering fatigue and creep analyses, however ambitious and expensive, are rarely useful and are often misleading in predicting cycling costs. Critical components for which detailed plant signature data are analyzed include: the steam drum, water wall /evaporator tubing, first/second pass water wall tubing, superheater and reheater tubing and headers, economizer inlet, and startup system components, as well as turbine/generator-related components, such as valves, cases, generator windings, and steam chests.

Heat Rate Effects

Careful measurement of unit heat rate cycling while at steady state indicates that there is significant degradation in unit heat rate when power plants cycle extensively. Poor efficiency comes from low load operation like load following, unit startups, and unit shutdowns. The rapid MW change causes undershoot and overshoot of critical boiler, balance-of-plant, and turbine temperatures, which leads to inefficiency and significant damage. The cumulative longer term effects of cycling can also increase the unit heat rate from causes like fouled heat exchangers, worn seals, and wear/tear on valves and controls. These cyclic heat rate effects can be seen in Figure 5. The resulting cost increase for a base-loaded plant is significant. Specifically, the true heat rate cost of cycling transients varies widely than one would compute from steady state heat rate test data and depending on capacity and loading factors, actual monthly heat rates exceed ideal constant-load test results.

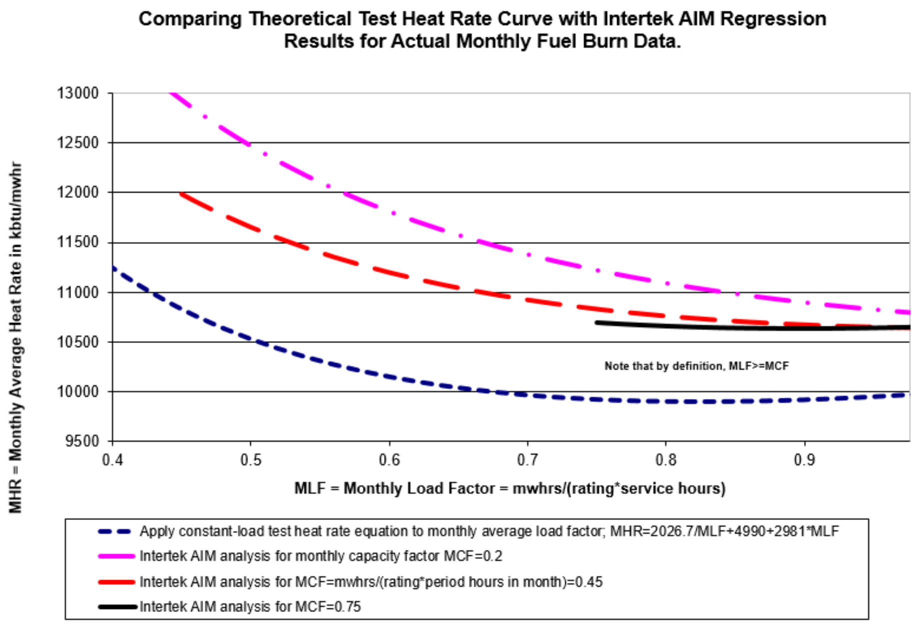

Figure 5 — Comparing Theoretical Test Heat Rate Curve with Intertek AIM Regression Results for Actual Monthly Fuel Burn Data.

POWER PLANT CYCLING COSTS

Some cycling costs are incurred immediately, such as those due to heat rate increases caused by a low and variable loading. However, wear out costs associated with equipment failures are almost always delayed at least by months and more probably by several years. For most units, we define these wear out costs as being associated with maintenance and capital equipment spending, along with the cost to replace power from forced outages due to equipment failure and degradation.

To determine unit cycling costs, damage modeling is combined with historical capital maintenance spending and unit loading over time to derive cost per unit-specific typical load cycle. Typically, annual capital and maintenance spending information for at least 10 years is evaluated, first by screening out costs not related to unit operation to arrive at annual candidate costs. In addition to this data, outage data and availability and outage cause is also typically evaluated for the entire operational period since unit startup. Using our statistical regression models to develop best estimates of the total unit equipment damage costs due to typical cycling, which include incremental EFOR, capital, and maintenance costs. These costs are first estimated for an equivalent hot start (EHS), and then estimated for the typical cycles experienced by the specific units studied based on how they are operated.

To independently corroborate the results of the regression analysis and to develop a deeper understanding of component specific cycling costs, an audit of work orders and historical spending is performed. By identifying the major costs of damage to components that currently contribute to the wear-and-tear elements of cycling costs, the calculated cost of cycling can also be adjusted in the future to reflect improvements made through changes in operating practices, component replacements, and upgrades. Figure 6 below shows the results of the regression analysis for the cost of cycling of a large coal plant. We included the impact of forced outages in this analysis, which resulted in a much lower coefficient of variance (COV) of 6% compared to 23% when we excluded the EFOR effect. This confirms our assertions that cycling causes increased forced outages. The impact of cycling related forced outages in this case was about $20,000 per EHS.

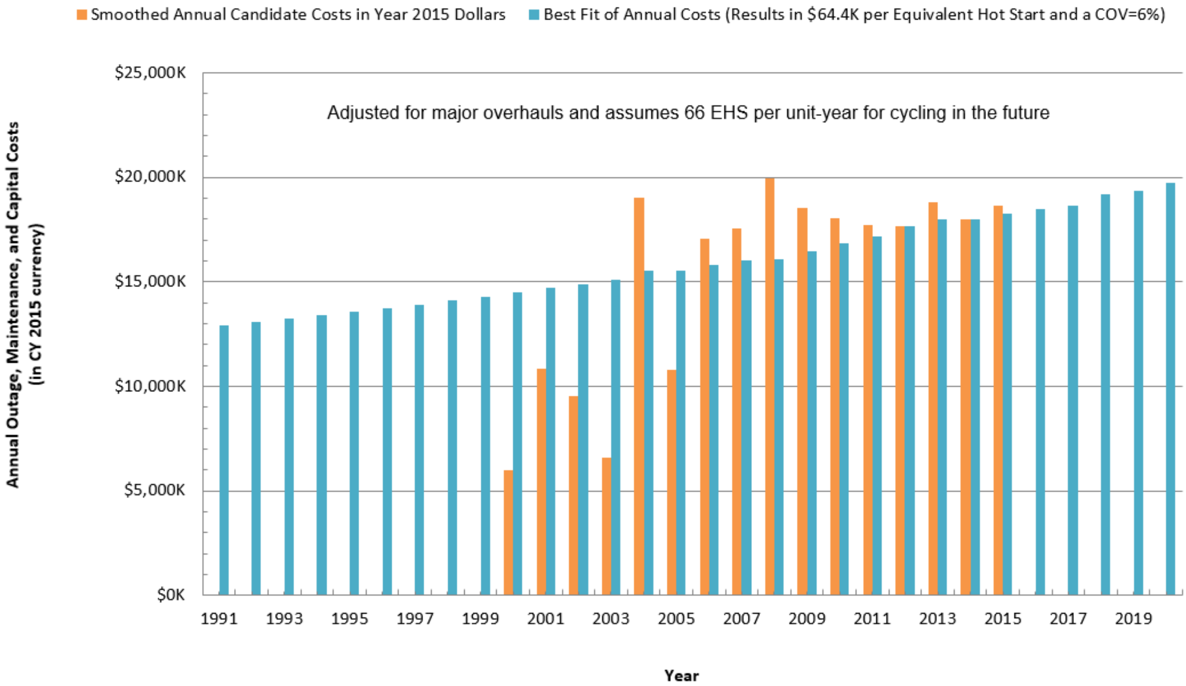

Figure 6 —Best Estimate of Intertek Example Unit Forced Outage, Maintenance, and Capital Costs.

A unit's specific analysis results depend heavily on the analysis of the historical capital and maintenance costs, past cycles and the unit signature data during cyclic operations, including the range of all load changes. The increased incremental costs that are attributed to cycling are broken down into the following categories:

- Increases in maintenance and overhaul capital expenditures
- Forced outage effects, including forced outage time, replacement energy, and capacity
- Cost of increased unit heat rate, both long-term efficiency, and while at low/variable loads
- Cost of startup fuel, auxiliary power, chemicals, and extra startup manpower
- Long-term generation capacity cost increases due to unit life shortening

CONCLUSIONS

Power plant operators should make dispatch decisions based on fuel production cost as well as cost of cycling to incorporate cycling damage and the lag times associated with this damage, and the dynamic heat rate effects discussed in this paper. Mission statements based on cyclic costs developed for each unit are useful in a fleet of power plants to define unit roles and optimize a group of units and, thus, reduce total costs.

System level benefits of including cycling costs can be significant. Utilizing cycling costs in dispatch models, a savings of $250,000 to $500,000 per week in overall costs could be achieved. In a large 25,000 MW system, Intertek AIM observed a 5-7% reduction in production costs when cycling costs were analyzed and included in optimal dispatch.

Increasing renewable generation on the grid and competition in the electric marketplace demands properly managing the power plant asset to perform cycling or baseload operations that are economically justified and profitable. This cannot be effectively done without a detailed cyclic cost analysis and careful control of operations and maintenance.